Nodeless superconductivity in the infinite-layer electron-doped $Sr_{0.9}La_{0.1}CuO_2$ cuprate superconductor

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We report on measurements of the in-plane magnetic penetration depth λ_{ab} in the infinite-layer electron-doped high-temperature cuprate superconductor $Sr_{0.9}La_{0.1}CuO_2$ by means of muon-spin rotation. The observed temperature and magnetic field dependences of λ_{ab} are consistent with the presence of a substantial $s-$wave component in the superconducting order parameter in good agreement with the results of tunneling, specific heat, and small-angle neutron scattering experiments.

I. INTRODUCTION

The symmetry of the superconducting energy gap is one of the essential issues for understanding the mechanism of high-temperature superconductivity. For hole-doped high-temperature cuprate superconductors (HTS's) it is commonly accepted that the superconducting energy gap has $d-$wave symmetry, as indicated, *e.g.*, by tricrystal experiments,[1] although a multicomponent ($d + s-$wave) gap is now acquiring overwhelming evidence.[2,3,4] For electron-doped HTS's, however, no consensus was reached on this issue so far. A number of experiments, including angular resolved photoemission,[5,6] scanning-SQUID,[7] Raman scattering,[8] and magnetic penetration depth studies[9,10] point to a $d-$wave, or more general, to a nonmonotonic $d-$wave gap (with the gap maximum in between the nodal and the antinodal points on the Fermi surface) in electron-doped $Nd_{2-x}Ce_xCuO_4$ and $Pr_{2-x}Ce_xCuO_4$. On the contrary, a state corresponding to an $s-$ or a nonmonotonic $s-$wave gap symmetry was reported for similar compounds and infinite-layer $Sr_{1-x}La_xCuO_2$ in tunnelling,[11,12] Raman scattering,[13] penetration depth,[14] small-angle neutron scattering,[15] and specific heat[16] studies. Results of Biswas *et al.*[17] and Skinta *et al.*[18] suggest that there is a $d-$ to $s-$wave transition across optimal doping in $Nd_{2-x}Ce_xCuO_4$ and $Pr_{2-x}Ce_xCuO_4$. The two-gap picture was also introduced in Refs. 19 and 20 in order to explain the unusual behavior of the magnetic penetration depth and Raman spectra.

Here we report a study of the in-plane magnetic field penetration depth λ_{ab} in the infinite-layer electron-doped superconductor $Sr_{0.9}La_{0.1}CuO_2$ by means of transverse-field muon-spin rotation (TF-μSR). This compound belongs to the family of electron-doped HTS's (Sr,Ln)CuO$_2$ (Ln=La, Sm, Nd, Gd) with the so-called infinite-layer structure.[21,22] It has the simplest crystal structure among all HTS's consisting of an infinite stacking of CuO$_2$ planes and (Sr, Ln) layers. The charge reservoir block, commonly present in HTS's, does not exist in the infinite-layer structure. It also has stoichiometric oxygen content without vacancies or interstitial oxygen,[23] which is a general problem for most of the electron- and the hole-doped HTS's. In the present study $\lambda_{ab}^{-2}(T)$ was reconstructed from the measured temperature dependences of the μSR linewidth by applying the numerical calculations of Brandt.[24] λ_{ab} was found to be almost field independent in contrast to the strong magnetic field dependence observed in the hole-doped HTS's, suggesting that there are no nodes in the superconducting energy gap of $Sr_{0.9}La_{0.1}CuO_2$. The temperature dependence of λ_{ab}^{-2} was found to be well described by anisotropic $s-$wave as well as by two-gap models ($d+s$ and $s+s$). In the case of the two-gap $d + s$ model the contribution of the $d-$wave gap to the total superfluid density was found to be of the order of 15%. Our results imply that a substantial $s-$wave component in the superconducting order parameter is present in $Sr_{0.9}La_{0.1}CuO_2$, in agreement with previously reported results of tunnelling,[12] specific heat,[16] and small-angle neutron scattering experiments.[15]

II. EXPERIMENTAL DETAILS

Details on the sample preparation for $Sr_{0.9}La_{0.1}CuO_2$ can be found elsewhere.[25] The TF-μSR experiments were performed at the πM3 beam line at the Paul Scherrer Institute (Villigen, Switzerland). The sintered $Sr_{0.9}La_{0.1}CuO_2$ sample was field cooled from above T_c to 1.6 K in a series of fields ranging from 50 mT to 0.64 T.

In the transverse-field geometry the local magnetic

field distribution $P(B)$ inside the superconducting sample in the mixed state, probed by means of TF-μSR, is determined by the values of the coherence length ξ and the magnetic field penetration depth λ. In extreme type-II superconductors ($\lambda \gg \xi$) $P(B)$ is almost independent on ξ and the second moment of $P(B)$ becomes proportional to $1/\lambda^4$.[24,26] In order to describe the asymmetric local magnetic field distribution $P(B)$ in the superconductor in the mixed state, the analysis of the data was based on a two component Gaussian fit of the μSR time spectra:[27]

$$P(t) = \sum_{i=1}^{2} A_i \exp(-\sigma_i^2 t^2/2) \cos(\gamma_\mu B_i t + \phi). \quad (1)$$

Here A_i, σ_i, and B_i are the asymmetry, the relaxation rate, and the mean field of the $i-$th component, $\gamma_\mu = 2\pi \times 135.5342$ MHz/T denotes the muon gyromagnetic ratio, and ϕ is the initial phase of the muon-spin ensemble. The total second moment of the μSR line was derived as:[27]

$$\langle \Delta B^2 \rangle = \frac{\sigma^2}{\gamma_\mu^2} = \sum_{i=1}^{2} \frac{A_i}{A_1 + A_2} \left[\frac{\sigma_i^2}{\gamma_\mu^2} + \left(B_i - \frac{A_i B_i}{A_1 + A_2} \right)^2 \right].$$
$$(2)$$

The superconducting part of the square root of the second moment σ_{sc} was further obtained by subtracting the contribution of the nuclear moments σ_{nm} measured at $T > T_c$ as $\sigma_{sc}^2 = \sigma^2 - \sigma_{nm}^2$.[28]

The following issue is important for the interpretation of the experimental data: The sample used in the experiment was a nonoriented sintered powder. In this case an effective averaged penetration depth λ_{eff} can be extracted. However, in highly anisotropic extreme type-II superconductors (as HTS's) λ_{eff} is dominated by the in-plane penetration depth so that $\lambda_{eff} \simeq 1.31\lambda_{ab}$.[29]

III. RESULTS AND DISCUSSIONS

Figure 1 shows the temperature dependences of $\sigma_{sc} \propto \lambda_{ab}^{-2}$ measured after field-cooling the sample from far above T_c in $\mu_0 H$=0.1 T, 0.3 T, and 0.6 T. Two features are clearly seen: (i) In the whole temperature region (from $T \simeq 1.6$ K up to T_c) $\sigma_{sc}(T,H)$ decreases with increasing field. (ii) The curvature of $\sigma_{sc}(T)$ changes with field. With decreasing temperature σ_{sc} at $\mu_0 H = 0.1$ T first increases and then becomes T independent for $T \lesssim$ 15 K, while σ_{sc} for both $\mu_0 H = 0.3$ T and $\mu_0 H = 0.6$ T increases continuously in the whole range of temperatures. It is also seen that the low-temperature slope of $\sigma_{sc}(T)$ is larger at the higher fields.

The decrease of σ_{sc} with increasing magnetic field is caused by the overlapping of the vortices by their cores, leading to a reduction of the field variance in the superconductor in the mixed state. As shown by Brandt,[24] at magnetic inductions $B/B_{c2} \lesssim 0.1$ (B_{c2} is the second critical field), overlapping of vortex cores may
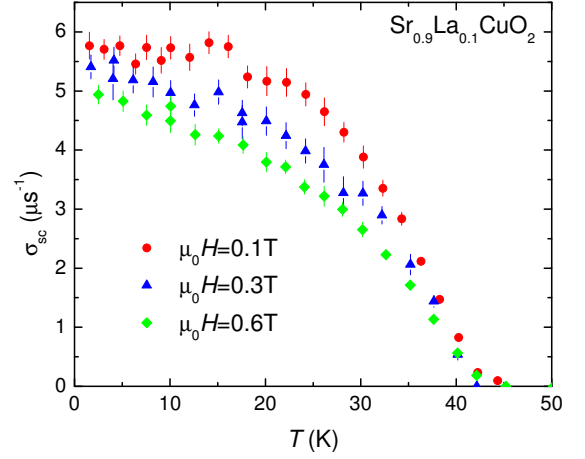

FIG. 1: (Color online) Temperature dependences of $\sigma_{sc} \propto \lambda_{ab}^{-2}$ of $Sr_{0.9}La_{0.1}CuO_2$ measured in magnetic fields of 0.1 T, 0.3 T, and 0.6 T.

be neglected and vortex properties are independent of the applied magnetic field. Only the vortex density is changed. At higher magnetic inductions vortices start to overlap by their cores. Consequently, not only the vortex density, but also the properties of the individual vortices become magnetic field dependent. Therefore, the different temperature behavior of σ_{sc} can be explained by the fact that the vortex core size, which is generally assumed to be equal to the coherence length $\xi = [\Phi_0/2\pi B_{c2}]^{0.5}$, increases with increasing temperature (decreasing B_{c2}). Thus higher temperature [bigger reduced field $b(T) = B/B_{c2}(T)$] would correspond to larger overlapping vortex cores leading to a stronger reduction of σ_{sc}. Consequently, the correcting factor between σ_{sc} and the magnetic field penetration depth is *not constant*, as is generally assumed, but depends on the reduced field b:[24]

$$\sigma_{sc}(b)[\mu s^{-1}] = A(b)\lambda_{eff}^{-2}[nm^{-2}]. \quad (3)$$

Here $A(b)$ is a correcting factor, which for superconductors with a Ginzburg-Landau parameter $\kappa = \lambda/\xi \geq 5$ in the range of fields $0.25/\kappa^{1.3} \lesssim b \leq 1$ can be obtained analytically as $A(b) = 4.83 \cdot 10^4 (1-b)[1+1.21(1-\sqrt{b})^3] \ \mu s^{-1} nm^2$.[24]

Equation (3) requires that in order to derive λ from measured $\sigma_{sc}(T)$, the temperature dependence of B_{c2} must be taken into account. Since in our experiments the measured λ_{eff} is determined by the in-plane component of the magnetic penetration depth λ_{ab} (see above), $B_{c2}(T)$ has to be measured with the magnetic field applied parallel to the crystallographic $c-$axis. The temperature dependence of $B_{c2}^{\|c}$ presented in Fig. 2 (a) was obtained from measurements of the reversible magnetization on the $c-$axis oriented powder by using the
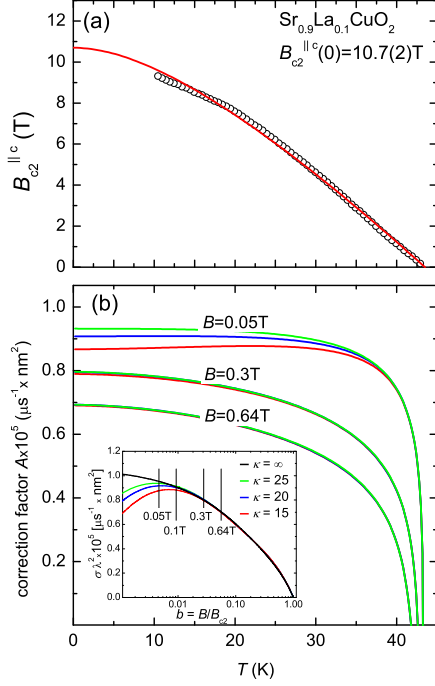
FIG. 2: (Color online)(a) Temperature dependence of the second critical field $B_{c2}^{\|c}(T)$ of $Sr_{0.9}La_{0.1}CuO_2$ obtained from measurements of the reversible magnetization on $c-$axis oriented powder by using the Landau-Ott approach.[30] The solid line is the fit of the Werthamer-Helfand-Hohenberg (WHH) model[31] to the data with $B_{c2}^{\|c}(0) = 10.7(2)$ T. (b) Temperature dependence of the correcting factor A at $B = 0.05$ T, 0.1 T, and 0.6 T for $\kappa = \lambda/\xi = 15$ (green line), 20 (blue line), and 25 (red line). The inset shows $A(b) = \sigma \cdot \lambda^2$ obtained from numerical calculations using the model of Brandt.[24] Vertical lines mark the values of $B/B_{c2}(0)$ for $B = 0.05$ T, 0.1 T, 0.3 T, and 0.64 T.

Landau-Ott scaling approach.[30] The solid line represents fit of $B_{c2}^{\|c}(T)$ using the Werthamer-Helfand-Hohenberg (WHH) model[31] with $B_{c2}^{\|c}(0) = 10.7(2)$ T. Note that $B_{c2}^{\|c}(0) = 10.7(2)$ T obtained in the present study is close to that reported in the literature.[32,33]

The correcting factor A [see Fig. 2 (b)] was calculated within the framework of the numerical Ginzburg-Landau approach developed by Brandt[24] in the following way. First, A was calculated as a function of the reduced field $b = B/B_{c2}$. The inset in Fig. 2 (b) shows $A(b) = \sigma \cdot \lambda^2$ [see Eq. (3)] for a superconductor with $\kappa = 15$, 20, and 25. Vertical lines correspond to $b = B/B_{c2}(0)$ for the fields used in the present study (0.05 T, 0.1 T, 0.3 T, and 0.64 T). Second, by using the calculated WHH form of $B_{c2}(T)$ [red solid line in Fig. 2 (a)], values of $A(T, B = const)$ for each particular field B were reconstructed. Figure 2 (b) shows the calculated $A(T, B)$ at $B = 0.05$ T, 0.1 T, and 0.64 T for $\kappa = 15$, 20, and 25.

Note that the influence of κ is only important at the lowest magnetic field ($B = 0.05$ T), while at the higher fields the effect of κ becomes almost negligible. This allows us to estimate the absolute value of λ_{eff} at low temperatures, which was found to be $\lambda_{eff} \simeq 120$ nm, in good agreement with previous results.[34] Bearing in mind that $\lambda_{eff} \simeq 1.31\lambda_{ab}$[29] and $B_{c2}^{\|c} = 10.7$ T [see Fig. 2 (a)], the Ginzburg-Landau parameter was estimated to be $\kappa \simeq 17$. This value of κ was used in the following calculations.
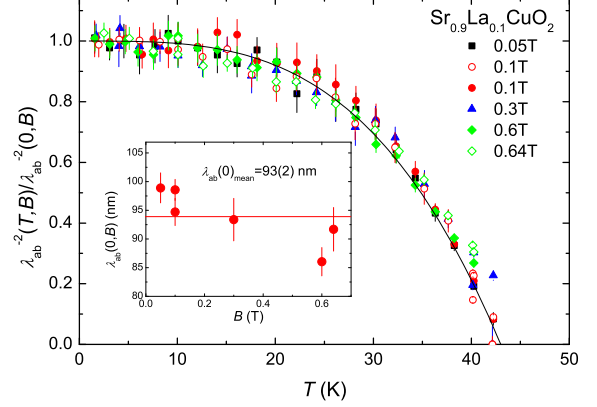

FIG. 3: (Color online) $\lambda_{ab}^{-2}(T, B)$ of $Sr_{0.9}La_{0.1}CuO_2$ normalized to their value at $T = 0$ reconstructed from $\sigma_{sc}(T)$ measured at $\mu_0 H = 0.05$ T, 0.1 T, 0.3 T, 0.6 T, and 0.64 T. The solid line is a guide to the eye. The inset shows $\lambda_{ab}(0)$ as a function of the applied filed.

The normalized $\lambda_{ab}^{-2}(T, B)/\lambda_{ab}^{-2}(0, B)$ curves reconstructed from the measured $\sigma_{sc}(T, B)$ are shown in Fig. 3. The inset shows $\lambda_{ab}(0, B)$ obtained from the linear extrapolation of $\lambda_{ab}^{-2}(T, B)$ at $T < 10$ K to zero temperature. It should be emphasized here that it has no sense to introduce any unique value of λ for each particular magnetic field, since only the zero-field value of λ has a physical meaning.[35] The same statement holds for the temperature behavior of λ^{-2}. This implies that if the theory used to reconstruct $\lambda(T)$ from $\sigma_{sc}(T)$ measured in various magnetic fields is correct, than the corresponding $\lambda(T)$ should *coincide*. The data presented in Fig. 3 reveal that this is the case. The normalized $\lambda_{ab}^{-2}(T, B)/\lambda_{ab}^{-2}(0, B)$ curves merge together and the value of λ_{ab} at $T = 0$, presented in the inset, is almost independent on the magnetic field. The small increase of $\lambda_{ab}(0)$ at low fields can be explained by the pinning effects which can lead to a reduction of the second moment of $P(B)$ in a powder HTS's at fields smaller than 0.1 T (see, *e.g.*, Refs. 28 and 36).

Fig. 4 shows $\lambda_{ab}^{-2}(T)$ reconstructed by means of the above described procedure from $\sigma_{sc}(T)$ for one representative field value $B = 0.1$ T. The data in Fig. 4 were analyzed by using single-gap and two-gap models, assuming that the superconducting energy gaps have the following symmetries: $d-$wave (a), anisotropic $d-$wave
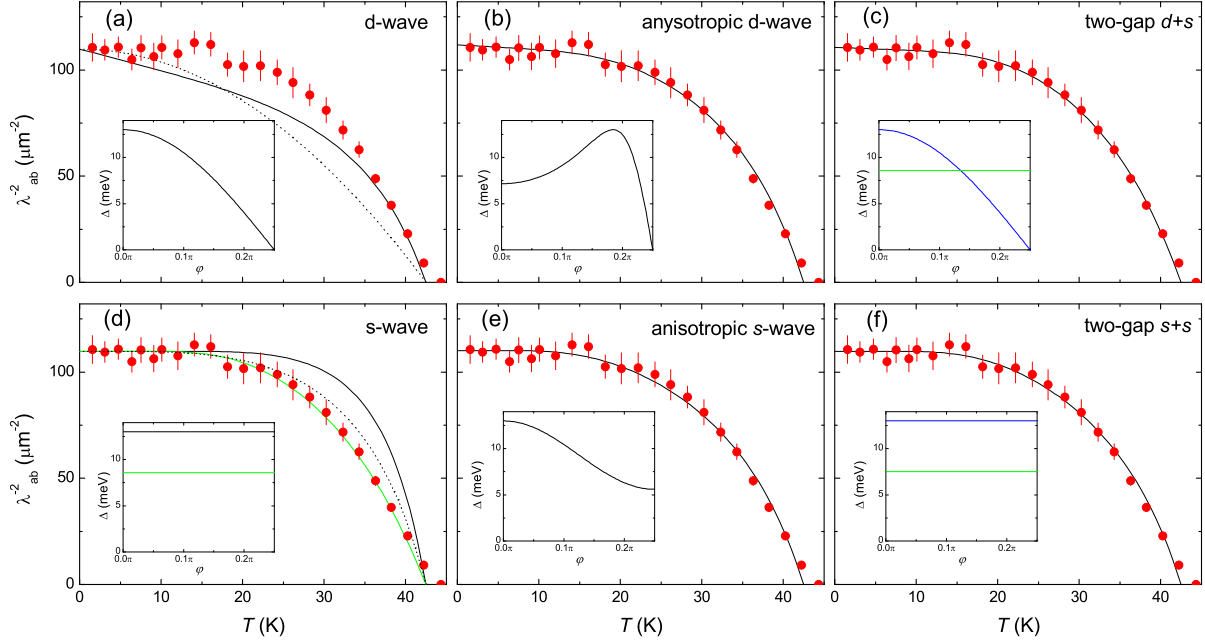
FIG. 4: (Color online) Temperature dependence of λ_{ab}^{-2} of $Sr_{0.9}La_{0.1}CuO_2$ reconstructed form $\sigma_{sc}(\mu_0 H = 0.1$ T). The curves were obtained within the following models of the gap symmetries: (a) clean $d-$wave (solid line) and dirty $d-$wave (dotted line), (b) anisotropic $d-$wave, (c) two-gap $d+s$, (d) clean $s-$wave (solid black – $\Delta_0 = 13$ meV and solid green – $\Delta_0 = 8.6$ meV) and dirty $s-$wave (dotted line), (e) anisotropic $s-$wave, (f) two-gap $s+s$. The corresponding angular dependences of the gaps are shown in the insets.

(b), $d+s-$wave (c), $s-$wave (d), anisotropic $s-$wave (e), and $s+s-$wave (f). The analysis for both the $d-$wave and the isotropic $s-$wave gaps was made in the clean ($\xi \gg l$, l is the mean-free path) and the dirty ($\xi \ll l$) limit. The cases of anisotropic $s-$ and $d-$wave gaps, as well as $s+s-$ and $d+s-$wave gap symmetries were analyzed in the clean limit only.

In the clean limit the temperature dependence of the magnetic penetration depth λ was calculated within the local (London) approximation ($\lambda \gg \xi$) by using the following equation:[2,37]

$$\left.\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)}\right|_{\text{clean}} = 1 + \frac{1}{\pi}\int_0^{2\pi}\int_{\Delta(T,\varphi)}^{\infty}\left(\frac{\partial f}{\partial E}\right)\frac{E\,dEd\varphi}{\sqrt{E^2 - \Delta(T,\varphi)^2}}. \quad (4)$$

Here $\lambda^{-2}(0)$ is the zero-temperature value of the magnetic penetration depth, $f = [1 + \exp(E/k_BT)]^{-1}$ is the Fermi function, φ is the angle along the Fermi surface ($\varphi = \pi/4$ corresponds to a zone diagonal), and $\Delta(T,\varphi) = \Delta_0\tilde{\Delta}(T/T_c)g(\varphi)$ (Δ_0 is the maximum gap value at $T = 0$). The temperature dependence of the gap is approximated by $\tilde{\Delta}(T/T_c) = \tanh\{1.82[1.018(T_c/T - 1)]^{0.51}\}$.[38] The function $g(\varphi)$ describes the angular dependence of the gap and is given by $g^s(\varphi) = 1$ for the $s-$wave gap, $g^d(\varphi) = |\cos(2\varphi)|$ gap for the $d-$wave gap, $g^{sAn}(\varphi) = (1 + a\cos 4\varphi)/(1 + a)$ for the anisotropic $s-$wave gap,[11]

and $g^{dAn}(\varphi) = 3\sqrt{3a}\cos 2\varphi/2(1 + a\cos^2\varphi)^{3/2}$ for the anisotropic $d-$wave gap.[39]

In the dirty-limit $\lambda^{-2}(T)$ was obtained via:[37]

$$\left.\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)}\right|_{\text{dirty }s-\text{wave}} = \frac{\Delta(T)}{\Delta(0)}\tanh\left[\frac{\Delta(T)}{2k_BT}\right], \quad (5)$$

and assuming the power low dependence

$$\left.\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)}\right|_{\text{dirty }d-\text{wave}} = 1 - \left(\frac{T}{T_c}\right)^n \quad (6)$$

with the exponent $n \equiv 2$,[40] for $s-$ and $d-$wave gaps, respectively.

The two-gap calculations ($d + s-$ and $s + s-$wave) were performed within the framework of the so called $\alpha-$model assuming that the total superfluid density is a sum of two components:[2,38]

$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = \omega \cdot \frac{\lambda^{-2}(T,\Delta_1)}{\lambda^{-2}(0,\Delta_1)} + (1 - \omega) \cdot \frac{\lambda^{-2}(T,\Delta_2)}{\lambda^{-2}(0,\Delta_2)}. \quad (7)$$

Here $\Delta_1(0)$ and $\Delta_2(0)$ are the zero-temperature values of the large and the small gap, respectively, and ω ($0 \leq \omega \leq 1$) is the weighting factor which represents the relative contribution of the larger gap to λ^{-2}.

The results of the analysis are presented in Fig. 4. The angular dependences of the gaps $[\Delta_0 \cdot g(\varphi)]$ are shown in

the corresponding insets. The maximum value of the gap $\Delta_0 = 13$ meV was kept fixed in accordance with the results of tunneling experiments.[12] It is obvious that simple $d-$ and $s-$wave approaches with $\Delta_0 = 13$ meV cannot describe the observed $\lambda_{ab}^{-2}(T)$ [see Figs. 4 (a) and (d)]. All other models as, *e.g.*, both anisotropic $d-$ and $s-$wave, and both two-gap $d + s$ and $s + s$ [Figs. 4 (b), (c), (e), (f)], as well as the single $s-$wave model with $\Delta_0 = 8.6$ meV [solid green line in Fig. 4 (a)] describe the experimental data reasonably well. The results of the analysis are summarized in Table I.

TABLE I: Summary of the gap analysis of the temperature dependences of λ_{ab}^{-2} for $Sr_{0.9}La_{0.1}CuO_2$. The meaning of the parameters is explained in the text.

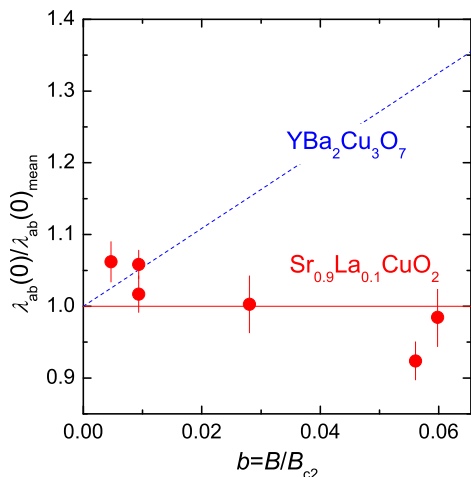| Model	$\Delta_{0,1}$ (meV)	a	$\Delta_{0,2}$ (meV)	ω
Clean limit s	8.6	–	–	–
Anisotropic d	13^a	3.1	–	–
Anisotropic s	13^a	0.4	–	–
Two-gap $d + s$	13^a	–	9.0	0.15
Two-gap $s + s$	13^a	–	7.5	0.35

^{a} From tunnelling experiments Ref. 12

FIG. 5: (Color online) $\lambda_{ab}(0)$ of $Sr_{0.9}La_{0.1}CuO_2$ normalized to its mean value as a function of reduced magnetic filed $b = B/B_{c2}$. The dashed blue line line corresponds to $\lambda_{ab}(0, b)$ for $YBa_2Cu_3O_{7-\delta}$ from Ref. 43.

Based on our analysis we cannot differentiate between the models presented in Figs. 4 (b), (c), (e), (f), and the isotropic $s-$wave model with $\Delta_0 = 8.6$ meV [solid green line in Fig. 4 (d)]. We believe, however, that from our consideration we can exclude the case of an anisotropic $d-$wave gap [see Fig. 4 (b)]. The reasons are the following: (i) The model of Brandt,[24] used to reconstruct $\lambda_{ab}^{-2}(T)$ from measured $\sigma_{sc}(T)$, is strictly valid for conventional superconductors only. The presence of nodes in the gap makes the electrodynamics of the mixed state highly nonlocal, leading to an additional source for decreasing the superfluid density due to excitation of the quasiparticles along the nodal directions (see, *e.g.*, Ref. 41 and references therein). In this case the proportionality coefficient A [see Eq. (3) and Fig. 2 (b)] depends much stronger on the reduced magnetic field and, as a consequence, on temperature than it is expected in a case of conventional superconductors. However, the normalized $\lambda_{ab}^{-2}(T, B)/\lambda_{ab}^{-2}(0, B)$ evaluated at various fields merge together (see Fig. 3), implying that $Sr_{0.9}La_{0.1}CuO_2$ can be, indeed, described within the model developed for conventional isotropic superconductors.[24] (ii) The nonlocal and the nonlinear response of the superconductor with nodes in the gap to the magnetic field leads to the fact that $\lambda_{ab}(0)$, evaluated from μSR experiments, becomes magnetic field dependent and increases with increasing field.[42] Such a behavior was observed in various hole-doped HTS's.[41,43,44] For comparison, in Fig. 5 we show $\lambda(0, b)$ for $Sr_{0.9}La_{0.1}CuO_2$ measured here and the one obtained by Sonier *et al.*[43] for hole-doped $YBa_2Cu_3O_{7-\delta}$. Whereas $\lambda_{ab}(0)$ for $YBa_2Cu_3O_{7-\delta}$ strongly increases with magnetic field, for $Sr_{0.9}La_{0.1}CuO_2$ it is almost field independent.

IV. SUMMARY AND CONCLUSIONS

Muon-spin rotation measurements were performed on the electron-doped high-temperature cuprate superconductor $Sr_{0.9}La_{0.1}CuO_2$ ($T_c \simeq 43$ K). $\lambda_{ab}^{-2}(T)$ was reconstructed from the measured temperature dependence of the μSR linewidth by using numerical calculations of Brandt.[24] The main results are: (i) The absolute value of the in-plane magnetic penetration depth λ_{ab} at $T = 0$ was found to be $\lambda_{ab}(0) = 93(2)$ nm. (ii) λ_{ab} is independent of the magnetic field in contrast to the strong magnetic field dependence observed in hole-doped HTS's. This suggests that there are no nodes in the superconducting energy gap of $Sr_{0.9}La_{0.1}CuO_2$. (iii) The temperature dependence of λ_{ab}^{-2} was found to be inconsistent with an isotropic $s-$wave as well as with a $d-$wave symmetry of the superconducting energy gap, in both the clean and the dirty limit. (iv) $\lambda_{ab}^{-2}(T)$ is well described by anisotropic $s-$wave and two-gap models ($d + s$ and $s + s$). In the case of the two-gap $d + s$ model the contribution of the $d-$wave gap to the total superfluid density was estimated to be $\simeq 15\%$. To conclude, a substantial $s-$wave component in the superconducting order parameter is present in $Sr_{0.9}La_{0.1}CuO_2$, in agreement with previously reported results of tunneling,[12] specific heat,[16] and small-angle neutron scattering experiments.[15]

V. ACKNOWLEDGMENTS

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